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"SPARKING CAVITY" Test report

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Introduction

One of the major concerns identified in the framework of the Neutrino-Factory study is the feasibility of very high gradient RF cavities which are exposed to high radiation. All scenarios rely on fast acceleration and cooling of the muon/pion beam of short lifetime. A net accelerating gradient of 5 MV/m is often stated as a design goal. The operational cavity surface field has therefore to reach about 10 MV/m.

This experiment is designed to provide information on the behaviour of an RF cavity in a high radiation field prior to the muon targetry and capture experiment at BNL, initially written as: "A proposal for an R&D Program for Targetry and Capture at a Muon-Collider Source" and now authorized as BNL experiment E951. C.D. Johnson (CERN) proposed to use the proton beam in the existing CERN/AD target area to irradiate the cavity under test (see his proposal: http://cdj.home.cern.ch/cdj/public/rf/Proposal.htm). A frequency at 200 MHz was chosen because of the availability of equipment.

It turned out that the maximum available beam intensity of the PS did not lead to a degradation of the RF voltage holding capability.

Details of the test conditions are given in the following paragraphs.

The AD target area

Figure 1 shows the part of the AD target area where the test cavity has been installed.

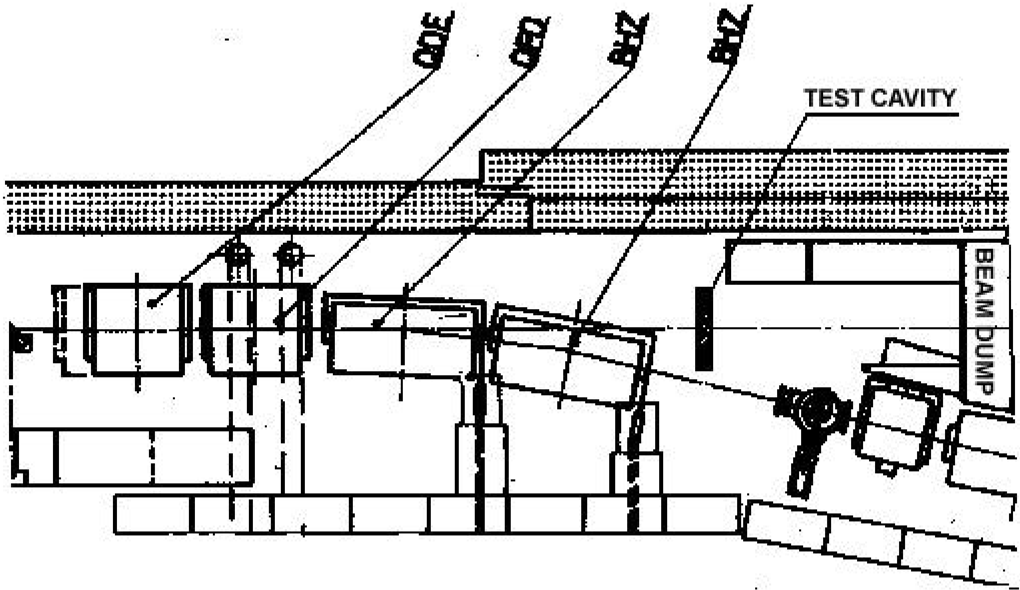
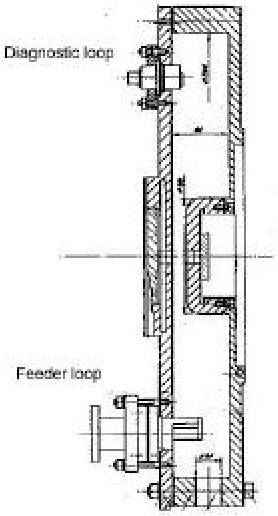


Figure 1: AD target area

The antiprotons are generated in a target from the proton beam and captured in a magnetic horn (parts not shown), enter the focusing quadrupoles QDE and QFO from the left and are deflected by the two bending magnets BHZ which are the first elements of the "dogleg" filter. The protons remaining behind the target follow an almost straight line and are collected in the water cooled beam dump at the right. The test cavity is located in front of the beam dump. Normally it receives protons parasitically without perturbing the antiproton beam to the AD. Alternatively the target can be taken out by remote control in which case the full proton beam hits the test cavity.



Cavity Parameters:

r/Q=31.5Ω
Q(theor)=15300
Q(meas)=~12000

Shunt impedance
r=382 kΩ

The test cavity

A vintage double buncher cavity resonating at 200/400MHz was taken as basis for the test cavity. The 400 MHz part together with the diagnostics port were removed and replaced by a welded plate or a screwed flange respectively to reestablish the vacuum tighness of the remaining 200 MHz section. Considering the high radiation level in which the cavity was bound to work, the TEFLON windows for the power and diagnostic coupling loops were replaced by POLYPENCO disks. Also the highly vulnerable tuner stepping motor was dismantled and a different tuning scheme implemented. The error signal from the usual tuner servo circuitry is now fed to a "stepping motor emulator" which acts on the master oscillator to adjust the operating frequency according to the uncorrected resonance frequency of the cavity. This inversion of the normal scheme is permissible for this stand-alone cavity since its RF phase needs not be synchronized with a beam or other accelerating structures.

A sketch of the modified 200 MHz cavity is shown in Fig. 2. The RF parameters were measured at low level with a network analyzer. The shunt impedance was evaluated by combining the measured Q-value with the calculated r/Q figure. An additional test using a direct gap voltage measurement was carried out to confirm the value of the shunt impedance; the data agree within about 7% (see Annex).

The cavity was mounted in a test hall with an existing amplifier chain as RF power generator of available output power of about 55 kW, feeder cable losses taken into account. The attainable RF voltage at the gap is then ~205 kV, corresponding to a field strength of 15.3 MV/m across the gap distance of 13.4 mm. This figure was initially considered as adequate since it covered the test goal of 10 MV/m.

Operation at full power without beam showed no sign of breakdown in the cavity.

Increase of the local field strength

The fact the cavity could not be brought to spark in the test setup was considered as unsatisfactory since no reference point was available for the expected degradation for operation with beam. An amplifier with higher power was unavailable. Instead the local field strength in the gap was increased by the addition of a field enhancement "finger" on the cavity axis (Fig. 3).

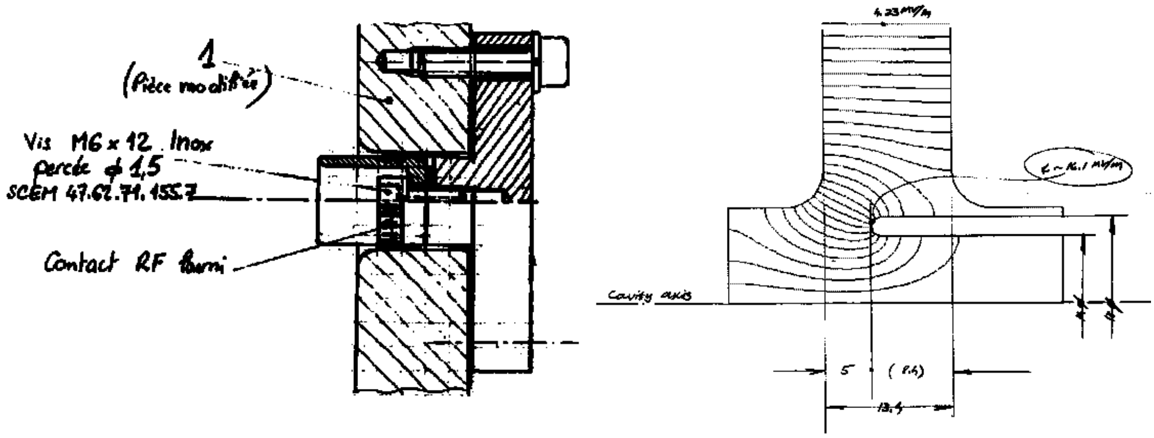


Figure 3: Finger insert (sketch of layout, left) and field configuration (SUPERFISH output, right)

The effect of the insert on the RF field has been investigated by calculations with SUPERFISH. The field enhancement is defined here as the ratio between the RF field strengths on the tip of the insert and in the flat part of the gap, respectively. This factor and the simultaneous detuning of the resonant frequency are very sensitive to the position of the insert, however this position is very difficult to measure with the necessary precision inside the closed cavity. On the other hand the detuning of the cavity resonant frequency is easily measurable and has therefore been taken as a more reliable quantity for the determination of the field enhancement. The results of the field calculations are shown in figure 4.

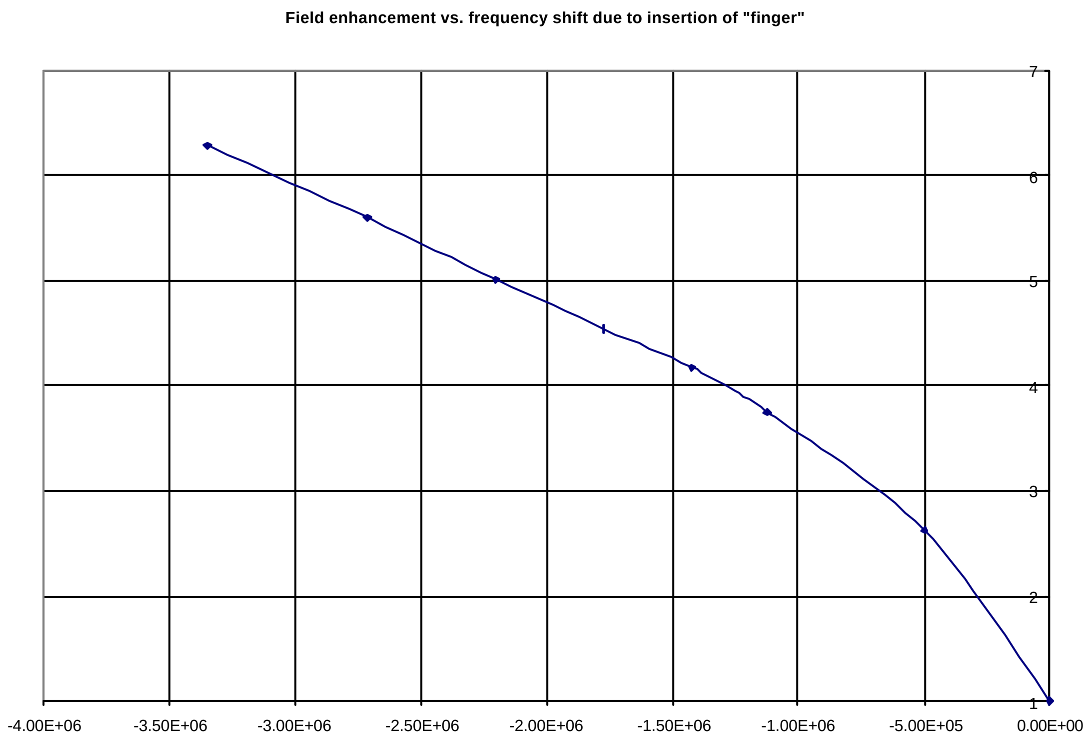


Figure 4: Field enhancement vs. cavity detuning for different positions of the finger insert

Initial power tests

The finger insert was mounted at several positions with increasing penetration until the cavity could be reliably driven to breakdown. At this position the detuning was -1.6 MHz, the corresponding field enhancement as high as 4.3.

It was initially planned to record the probability of breakdown as a function of RF field. A dedicated PC based data acquisition system has been provided for this purpose. It was however found that the transition between the regimes of reliable voltage holding and continuing sparking was very abrupt and occurring within a field level of the order of a few percent. No reproducible sparking profile could be measured within this band.

After suitable cavity conditioning the field level for virtually zero breakdown rate was determined. The corresponding peak surface field was about 47 MV/m, i.e. 3.15 times the Kilpatrick limit (frequency 199.7 MHz, RF pulse length 200μs, pulse rate 2pps).

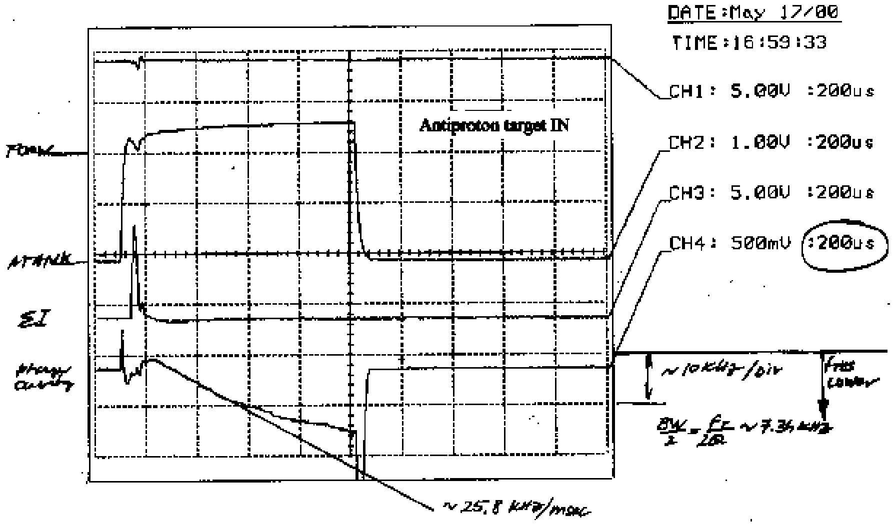


Figure 5: Cavity response, target

Tests with beam

The cavity was installed in the underground AD target area, with the amplifiers mounted at a distance of about 22 m at the surface in Hall 195. A dedicated timing allowed to start the RF envelope of the cavity with adjustable advance or delay with respect to the beam pulses occurring at intervals of 100 to 200 seconds. Asynchronous test pulses in the beam pauses at a rate of about 1 pps allowed to check the cavity conditions permanently. Servos for amplitude/phase/tuning were normally active to compensate for long-term drifts, but were switched off during the beam pulse to show all perturbations without correction. The vacuum in the cavity was stable at 4.5E-8 torr.

The record of a pulse with beam is shown in Fig. 5 (left).The traces show from top to bottom

- beam prewarning pulse (high: beam present),
- cavity response"ATANK", the cavity field whose amplitude is adjusted close to sparking,
- magnetic horn current, indicator of beam passage,
- cavity phase.

Full field is held also after arrival of the beam, in no case a beam induced breakdown was observed.

The small dip in all traces at beam time stems from electromagnetic interference and is not related to the real behavior of the cavity. The equipment was located in close proximity to the pulsed power supplies of the magnetic horn of the AD target. Spurious signals are induced in all cables. Despite of careful grounding and shielding, many difficulties were encountered with false triggering in equipment accepting the usual inverted TTL signals.

Drift of cavity phase

The lowest trace in Fig. 5 shows a significant drift of the cavity phase following the impact of a beam pulse. The sign of the phase deviation indicates a shift of the cavity resonance towards lower frequency, the drift speed corresponds to about 3.5 times the 45° cavity (half) bandwidth per millisecond (see calibration at the right border).

Note that the drift continues steadily after the short duration of the beam pulse (the total duration of the beam burst is about 0.5 µs which corresponds roughly to the width of the trace). Different RF timing shows that the dephasing starts with the beam pulse independently from the position of the RF cycle, that acts only as a sampling pulse for the tuning state. It takes about ten seconds for the cavity to return to the initial frequency of resonance. If the delay between beam and RF is in the order of a fraction of a second, it may be impossible to get any cavity response at the nominal generator frequency as a result of the strong detuning in presence of a multipactor barrier.

The cavity amplitude in Fig. 5 *increases* slightly after the impact of the beam. Here the generator frequency was adjusted slightly too low. The cavity was therefore initially tuned too high but drifted to resonance, hence to maximum response, under the influence of the beam impact.

The precise mechanism of the cavity drift is unclear. Considering the long time constant, the asymptotic non-oscillatory behavior and the independence from RF timing , the most plausible explanation is a mechanical/thermal effect, probably caused by elongation of the field enhancement finger due to the energy deposited by the beam.

Tests with AD target removed

Figure 6 shows the same traces as Figure 5, but with the AD target removed (note the different scale factors !). The drift of the cavity is more almost 6 times higher, the voltage holding capability is nevertheless intact.

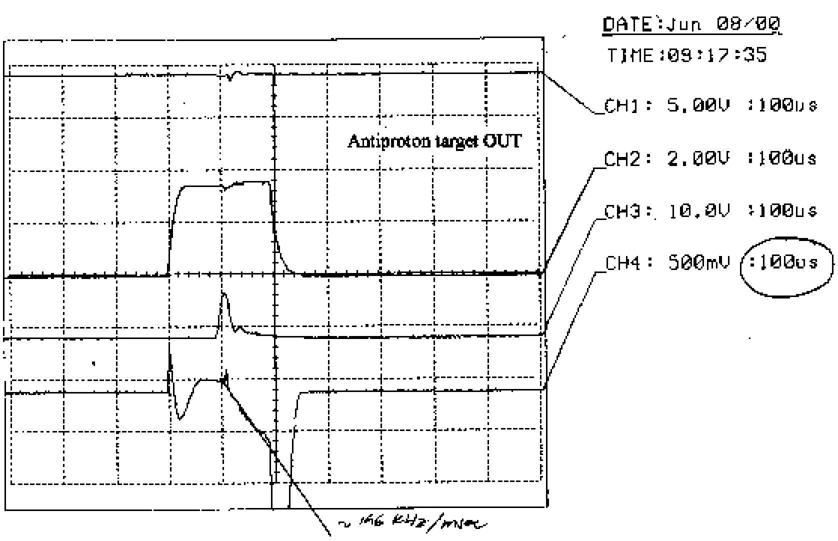


Fig.6: Cavity response, target OUT

The higher drift hints at a considerably higher beam intensity hitting the cavity. The AD target consists of a cylinder, 50 mm long, made of iridium and some carbon. When in place, some intensity is lost therein but the main effect is a much larger divergence of the outgoing proton beam. This leads to strong collimation by the limited aperture of the downstream equipment. With the target in place, the readings of the beam transformer immediately behind the magnetic horn are decreased by a factor of about two; it is plausible that additional beam losses of about the same magnitude occur in the downstream beam line of 7 m length containing four magnets of small aperture.

Radiation aspects

The fluence and dose absorbed by the cavity were studied using activation techniques and alanine dosimeters. The front of the cavity was equipped with aluminum, nickel and cobalt foil activation monitors, together with alanine cable and Radiochromic-Dye film from Riso National Laboratory (Denmark). A detailed description of these monitors and their readings can be found in the internal CERN report TIS-RP/TM/00-32.

The cavity remained 44 days in the target area, was exposed to about 10 000 pulses and absorbed a total dose in excess of 500 kGy (alamine saturation level). Taking into account the total received fluence together with the number of beam pulses, it follows that a single pulse comprised approximately 5E12 protons at the cavity. This figure is about 1/3 of the protons impinging on the target (1.5E13 in 4 bunches, each 30 ns long, bunch spacing 105 ns). Possible reasons for the loss are explained above.

Beam offset

A picture of the cavity with installed radiation monitors is shown in Fig. 7 (left). From this photograph and from the readings of the aluminum dosimeter foils it is evident that the beam did not hit the cavity center, but was horizontally offset by about 10 cm towards the (West) wall. The cavity was aligned in a straight line from the center of the target to the beam dump. Apart from an alignment error the observed offset can be explained by the deflection of the proton beam by the two dipole magnets which bend the antiproton beam in the opposite direction. The beam center hit the cavity at the edge of the flat gap region, with the finger insert situated only at the periphery of the beam.

Fig.7: Cavity with foil activation monitors, alamine dosimeter cables and radiation sensitive film

Discussion of the results

The cavity has reached the surprisingly high RF field of 3.15 times the Kilpatrick limit. All calibrations have been carried out with great care; however it is intended to repeat the calibrations as a double check as soon as the cavity has sufficiently cooled down to allow access. It is well known, on the other hand, that local field enhancement as in this test setup has often only little influence on RF breakdown so the quoted high field limit is gaining additional credibility.

No difference in the sparking limit was observed with or without impinging beam. This is in itself an encouraging result, regardless of the precise absolute value of the common sparking limit.

Altough the maximum particle flux presently available at CERN has been used for the tests, it is still far inferior to what has to be expected in a Neutrino Factory. Due to the fact that the beam was offset from the cavity center, its effect on the RF field was further reduced..

If some fast ignition mechanism is hypothesized then only the number of impinging particles in a time window around the maximum instantaneous cavity voltage is important. The breakdown limit then depends primarily on the number of particles passing *during one RF period (or part thereof)*, and the primary cause for the breakdown under radiation would be "particle flux/ RF frequency". The tests at the relatively high frequency of 200 MHz become too optimistic for the 40/80 MHz scenario.

Erosion problems may arise from long term exposure of the cavity to intense beams; this issue cannot be addressed under the present circumstances.

Repeating the tests is under consideration. Improvements of the test setup would comprise a larger gap area with a more uniform RF field, dedicated recording of the received beam pulses, modified alignment to take the deviation of the proton beam into account, and possibly an aluminum cavity body sandwiched between solenoid coils to study the combined effect of beam and magnetic field on the breakdown limit.

Acknowledgements

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ANNEX

Calibration of the Sparking Test Cavity

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1 - Introduction

Each RF cavity is defined by 3 parameters:

- its resonance frequency : $\mathbf{f_0}$,
- its **Q** factor,
- its shunt impedance: $\mathbf{r_{shunt}}$.

In addition, the feeder loop and diagnostic ports have to be calibrated. The respective procedures followed for the calibration of the sparking test cavity as outlined below.

2 - Resonance frequency measurement

By direct measurement with a network analyzer, we have found the resonance frequency of the cavity: resonance peak of transmission between two coupling loops has appeared on a log amplitude vs. frequency display. This peak was centered on

$\mathbf{f_0 = 204.823\ MHz}$.

The tuning range using the motorized tuner was 175 kHz.

3 - Q factor measurement

2 methods exist to measure this factor :

- by reflexion,
- by transmission.

3.1 - By reflexion (45°; points on Smith chart)

First we need to check the adaptation of the cavity. On a Smith chart we can read the input impedance of the cavity. We had to turn the power loop until a virtually perfect matching was obtained, i.e. until the circle describing the cavity input impedance intersected the real axis at the center of the Smith chart. Then we add electronically a phase offset to simulate a measurement at the "detuned short" plane of the feeder line, i.e. a position where the fully detuned cavity appears as a short circuit. The cavity impedance at resonance is then purely resistive, its ratio with respect to the generator impedance the well-known "β factor".

Next step is to read the frequency at the 45°, points. At this points we have imaginary and real part of the impedance having the same value. The difference of frequency, Δf. The Q-factor is defined by:

$Q_0 = f_0/\Delta f$

The loading of the cavity by the generator impedance does not influence the measurement, since the directional coupler measures only the downstream part of the setup, hence no β correction needed : the formula above can be directly applied.
We have measured

1st 45°; point: 206.484 MHz
2nd 45°; point: 206.501 MHz
Δf = 17 kHz
resonance frequency : 206.492 MHz

$Q_0 = f_0/Df = 206.492E6/17E3 = 12147$

3.2 - By transmission (-3 dB points)

We have determined the points around the resonance peak at -3 dB from the maximum value. The results are :

f_0 = 200.947 MHz
left -3 dB point at -17.275 kHz from peak
right -3 dB point at 17.012 kHz from peak

Then:

$Q_L = f_0 / \Delta f = 200.947E6/(17.275E3+17.012E3) = 5861$

The factor measured is Q loaded, since the cavity is loaded by the generator. We need to use 'β correction" to find Q_0 using the well-known formula:

$Q_0=Q_L(1+\beta)$

where $\beta = r_{in}/Z$ (r_{in} = input impedance of the cavity measured at the "detuned short" plane of the feeder line / Z = generator impedance).
The power loop has been adjusted to β = 1 (perfect motor)in the previous step, hence:

$Q_0=5861(1+1)=11722$

4 - r shunt measurement

The shunt impedance has been measured by two different methods:

- use calculated r/Q and measured Q to calculate r_{shunt} =(r/Q)*Q,
- direct measurement of field in gap.

4.1 - r/Q calculated

The simulation of electromagnetic field in gap by the program SUPERFISH gives us the following value of r/Q : 31.47 Ω.

With Q measured in paragraph 2.1,

r_{shunt} = (r/Q) * Q = 31.47*12E3 = 382,3 kW.

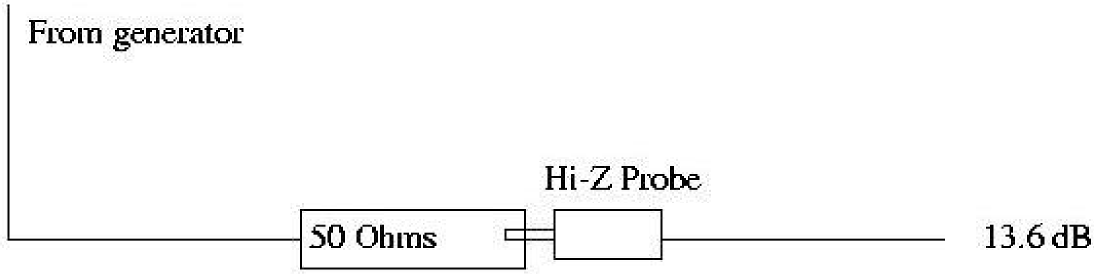
4.2 - Direct measurement of field in gap

The shunt impedance r_s, "equivalent circuit definition", is defined as :

$r_s = U_{gap}^2 / (2*P)$

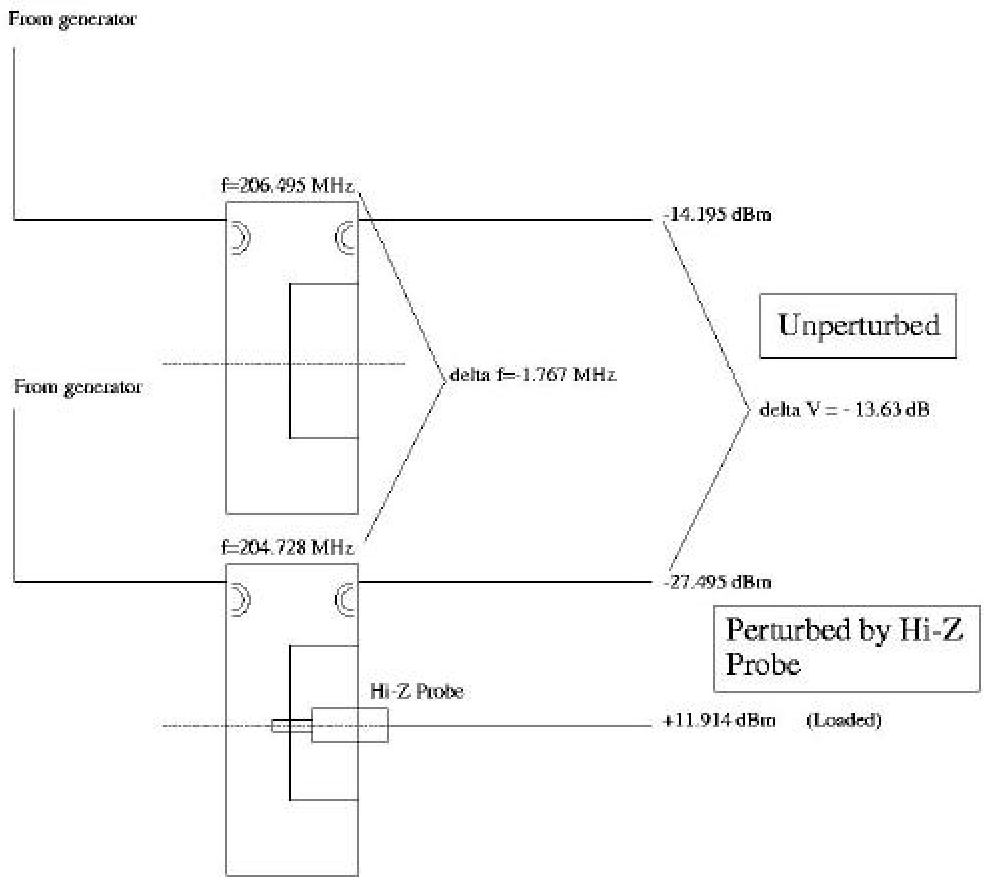
where U_{gap} = peak RF voltage developed at the cavity gap for a given input power P. A high impedance "Hi-Z" probe is used to measure the voltage across the gap. However, the loading of the cavity by the finite probe impedance has to be taken into account. The following procedure has been applied to correct for this effect.

4.2.1 - Calibration of the pobe



This determines the relative probe response V, for the given (constant) generator level across an impedance of 50 Ω.

4.2.2 - Determination of the field perturbation by the probe



All RF level measurements are referred to generator forward wave

The cavity is fed by the power loop and the cavity field measured by the built-in diagnostic loop, first unperturbed, then with the Hi-Z probe at the gap. This shifts the resonance frequency as well as the field amplitude.

The differences are:

Δf = - 1.1767 MHz
ΔV = - 13.63 dB

The (perturbed) voltage reading of the Hi-Z probe is :

V_2 = 11.91 dB

hence the "real" unperturbed gap voltage:

$V_3 = V_2 - \Delta V = 11.91 - (-13.63) = 25.54$ dB

4.2.3 - Calculation of the shunt impedance

For a given constant input power, the developed voltages V_x, V_y at different load impedances r_x, r_y are related by:

$r_x / r_y = (V_x / V_y)^2$

Hence,

$r_x = r_s$	$r_y = 50\ \Omega$
$V_x = V_3 = +23.54$ dB	$V_y = V_1 = -13.6$ dB

$r_s = 50\ (V_3/V_1)^2$
$(V_x/V_y)_{dB} = 25.54 - (-13.597) = 39.13$ dB
$V_3/V_1 = 10^{(39.13/20)} = 90.47$
$\mathbf{r_s = 50*(90.47)^2 = 409.2\ kW}$

This is ~7% higher than the figure obtained by method 3.1.

5 - Test loop calibration

The RF chain needs a return signal of about 2 W (~ -33dBm) for proper operation of the servo circuits. Supposing a nominal cavity power of 40 kW (~76 dBm), the total return loss between power loop and test loop should be about 43 dB. To allow a margin for cable losses and additional local attenuation, the test loop level has been adjusted to 34 dB below feeder loop input.

Note: During high power tests, these were discrepancies between the power feed for the cavity (as read by independent devices) and the reading at this loop. This calibration test will be repeated as soon as the radiation level of the cavity will permit access.